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STEAM BOILER EXPLOSIONS.

BY

ZERAH COLBURN.

Edited, with an Introduction, by

ROBERT H. THURSTON.

NEW YORK
D. VAN NOSTRAND COMPANY,
23 MURRAY AND 27 WARREN STREET.
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INTRODUCTION.

THE following little treatise on the subject of Steam-boiler Explosions is a "classic" in its department of engineering literature. Its author, ZERAH COLBURN, was one of the most remarkable and most talented men that the constructive profession has ever known. Descended from a family noted for its intelligence, and especially for talent in mathematics and the sciences, he fully sustained its reputation. For many years connected with that famous periodical the "*London Engineer*," he finally severed his connection with it, to found another now no less famous journal, "*Engineering*." This he promptly made a success in all respects, and a success it remains to-day, in the hands of Messrs. Maw and Dredge, his hardly less talented and en-

terprising lieutenants. He broke down from over-work, after a time, and remained in a state of nerve-exhaustion for two years or more, able to do little or no work on his new journal, and sustained only by the life, energy, and ambition of his two aids, and his friend the publisher of the paper. He at last came to his early home, in America, and there died, leaving a record, short though it was, that most men might well envy.

His work and the monuments of industry and ability which he has left behind him have peculiar interest to Americans; not simply because of his own connection with us by birth and early training, but because he never forgot his interest in his own country or his own countrymen. At a time when it was felt, by many of his colleagues in the profession and compatriots from the United States, that it was difficult to secure fair recognition in England for good work done, or for the great inventions that were seeking continually to find introduction there, and when every one felt, visiting that

country, that the feeling toward the American Cousin was not always kindly, and that the latter sometimes had reason to feel that he was not always, not often, in fact, given a generous reception, on that side the Atlantic, by those who should be his best and warmest friends, his brothers of the blood, Zerah Colburn told the writer that he intended that, in the columns of the new paper, especial care should be taken to give to America and to Americans ample space and fair hearing ; that the cousins from the West should have kindly welcome on all occasions, and a thoroughly honest and generous treatment. National prejudice, mistaken patriotism, petty jealousy, should never shut out the brother-inventor, the fellow-mechanic, the colleague in engineering of this side the Atlantic, from the English heart or British shops, so long as his journal should endure. And he well redeemed his promise ; and well have his heirs and assigns redeemed it. That attitude on his part preceded a very complete change in that of the Brit-

ish press and the British people toward America and Americans, and toward the work of the American engineer and mechanic. The devices of the "Yankee" inventor are now nowhere more heartily and wholesomely received than by the better class of British technical journals. British practitioners have usually been fair and generous in their judgments of their cousins on this side the water.

Colburn, as a matter of course, in organizing and promoting a new scientific periodical, found himself compelled to do a very large part of the work of writing for the paper himself. But he secured, in this work, the aid and the countenance of many of the best engineers on both sides the ocean, and was especially fortunate in obtaining the assistance of his old friend Alexander Holley, than whom no one could have wielded a more facile and productive pen. The paper became promptly known in the United States as the friend of every American visiting London, and as the advocate of all worthy American enter-

prises and inventions. Its circulation in the United States was promptly established, and it has never lost even its rate of gain in this constituency. But Colburn never had the comfort of seeing what a marvellous growth had come of the seed so hopefully, but desperately, planted by him.

In the course of his work, he had paid much attention to the various departments of steam-engineering, having been, with his friend Holley, especially interested in railroads ; and this led him to the study of the subject of steam-boiler explosions, as one of peculiar importance and interest to the engineer as well as to the public. A suggestion made by Mr. Daniel Kinnear Clark, the now veteran engineer and author, led him to the development of a theory of the method of explosion, in a certain class of cases, which has since been generally known as the Colburn Theory, or, more properly, as the Theory of Clark and Colburn. It is this hypothesis which he sought to present clearly in the monograph on the

subject which is here printed and published.

First published about 1860, it remains the only special treatise on the Colburn and Clark Theory in the English language, and it has been thought by the publishers, and by many engineers as well, desirable that it should not be allowed to pass entirely out of print. This is the more advisable, that, in later years, new evidence has been obtained bearing upon that main argument, and, also, upon the thousand minor points which are grouped around it, in the study of the more general aspects of the phenomena of boiler decay and disruption. The writer, who happens to have paid some attention to the same subject, and to have collected considerable material into the form of a treatise of larger extent, recently published, has been requested to edit this edition of this little tract, for that most valuable series of monographs, the "VAN NOSTRAND SCIENCE SERIES," and to add, in the form of footnotes, such references as may enable the reader who

may be sufficiently interested in the matter to do so, to read evidence collected to date, in some detail. These references are mainly to the writer's larger work, "MANUAL OF STEAM-BOILERS; THEIR DESIGN, CONSTRUCTION, AND OPERATION," published in 1889 (last edition) by the Messrs. Wiley, and sold by The Van Nostrand Company. Where the reference is made to the *"Manual,"* it is this treatise which is intended.

For still other and detailed information, the reader may consult the little work of Mr. J. R. Robinson, and the various fugitive essays to be found in periodicals, as referred to in the larger work to which reference is mainly had. The report on the work of Mr. Lawson, which is probably the first and only direct experimental proof of the possibility of exploding a boiler by a process analogous to that which the far-seeing mind of Colburn had indicated, will be found to be of extraordinary interest in this connection. The fulness with which original authorities have been cited in the

Manual makes it quite unnecessary to increase the bulk of this little tract by repeating them here.

R. H. Thurston.

Director's Rooms,
Sibley College, Cornell University,
January 1, 1890.

STEAM-BOILER EXPLOSIONS.

A WELL-MADE steam-boiler cannot be burst or torn open except by a great force. The internal pressure required to rend open a cylindrical boiler may be approximately calculated for any size of boiler and thickness of plates. With a boiler 3 ft. in diameter and 10 ft. long, the plates, if $\frac{3}{8}$ in. thick and riveted in the ordinary manner, oppose at least $65\frac{1}{2}$ sq. in. of resisting section to any pressure tending to burst the boiler longitudinally open, or in the direction of its least resistance. A section of $65\frac{1}{2}$ sq. in. of iron, of average quality, would not yield under a tensile stress of much less than 1,462 tons (the resistance of the iron being taken as 50,000 lbs. per sq. in.), and this amount of stress could not be exerted by the steam within a boiler of the assumed di-

mensions, except at a pressure of at least 758 lbs. per sq. in. Such a boiler, therefore, if worked at a pressure of less than 125 lbs. per. sq. in., would appear to be beyond all danger of explosion.

This very large apparent margin of strength has been taken by many as sufficient to justify the hypothesis of some violent internal action, at the instant preceding the actual rupture of a steam-boiler; the rupture being regarded as the consequence of such action, and not of a mere pressure; which, until the ruptured parts are in motion, can only act statically. In hypotheses of this kind, electrical action, the detonation of explosive gases assumed to be collected within the boiler, and the sudden production of steam from water thrown on hot plates, have been variously assigned as the causes of internal concussion. Such hypotheses have derived a certain amount of probability from the fact that there are perhaps as frequent instances of the quiet rupture of steam-boilers as there are of their violent explosion. A simple rupture, at-

tended only by the loss of the steam and water in the boiler, can of course occur only (under the ordinary working pressure) in consequence of the failure of a particular plate or seam of rivets; either from original defects in the material, imperfect construction, or from some injury which the boiler has sustained either at or before the moment of rupture. Such ruptures, being but rarely attended by any serious consequences, are seldom publicly reported. Their frequent occurrence, however, might appear to exhaust the explanation by overpressure, so perseveringly urged by Mr. Fairbairn and others in all instances of the violent explosion of steam-boilers.

Without, however, at present considering ourselves bound either to accept or to reject the explanation of steam-boiler explosions by steadily accumulated pressure, we may consider the probability or otherwise of the various explanations which assume the sudden production of great quantities of steam from water thrown upon red-hot plates; electrical action; the

decomposition of steam and detonation of hydrogen in contact with air, etc. etc.

Overheating.—Although it is possible that boilers may be exploded, in consequence of the formation of a great quantity of steam from water thrown upon red-hot plates,* overheating cannot be assumed as being the general cause of explosions, which very frequently occur where there is abundant evidence, both before and after the disaster, that no overheating has taken place. Explosions have happened in many cases when, but a moment before, the water-gauges indicated an ample supply of water; and in such cases, as well as in others, where there was positive evidence as to the amount of water in the boiler, the furnace-plates have been found in a perfectly sound state, or at least without any appearance of having been burnt. Burnt iron can be recognized without difficulty, and the fact that the plates of an exploded boiler show no signs of having

* See Report of Committee of the Franklin Institute; Journal, 1836. Manual of Steam Boilers, p. 568.

been burnt may be taken generally as proof that they have never been overheated after having been made up in the boiler of which they formed a part.

Supposing, however, extensive and severe overheating to have taken place, and water to be suddenly thrown upon the heated plates, it is doubtful if the quantity of steam disengaged would be sufficient to increase greatly the pressure already within the boiler.* Whoever has observed a large mass of wrought iron, when plunged at a high heat into twice or three times its weight of cold water, must have remarked how small a quantity of steam was disengaged. There is reason to believe that just as much and no more steam would be produced if the same weight of iron, heated to the same degree, were disposed in the form of a boiler, and the same quantity of cold water were suddenly thrown into it. If, however, the boiler already contained a considerable quantity of water, heated to from 212 deg. to 400 deg., the injection

* Probably an error. See Manual, p. 567; § 277.—Ed.

of additional water, upon any overheated surface of the furnace might be followed, as indeed, in such cases, it often is, by an explosion. The effects produced upon the sudden liberation of a great quantity of heat, stored up, under considerable pressure, in the water contained in a steam boiler, will be considered in another part of the present paper. But there is, I think, sufficient reason to believe that an empty boiler, however much it may be overheated, may be filled, or partly filled, with water with no danger whatever of explosion. Red-hot boilers, I am told, have been occasionally filled in this way without any disturbance or consequences of any kind indicating a tendency to explosion. I have never tried such an experiment myself, nor can I, perhaps, furnish such authority as would, by itself, be sufficient to establish such a fact;* but a brief con-

* A letter appeared in "The Engineer" of April 3d, 1857, signed "James Johnstone," and containing the following statement:—"In the course of my investigations I have obtained information that will be of use to your correspondent, 'J. H., jun.,' who, I perceive by

sideration of some of the phenomena of heat has convinced me that it is a fact. The actual quantity of heat which the thin metallic sides of a steam-boiler are capable of containing, is not sufficient to change a very large quantity of water into steam. According to the best authorities, the amount or total quantity of heat which would raise the temperature of one hundredweight (112 lbs.) of iron, through one degree, would impart the same additional temperature to $12\frac{1}{2}$ lbs. only of water. The quantity of heat which would raise the temperature of one hundredweight of copper through one degree would raise that of $10\frac{2}{3}$ lbs. only of water to the same extent. Thus,

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your last number, is about to fill a red-hot boiler with water by way of experiment. That has been done, and the result surprised the witnesses. The boiler was 25 ft. long, 6 ft. diameter, and the safety-valve loaded to 60 lbs. per sq. in. When empty and red-hot the feed was let on and the boiler filled up. No explosion occurred, but the sudden contraction of the overheated iron caused the water to pour out in streams at every seam and rivet as far up as the fire-mark extended." In an editorial article which appeared in the "Scientific American" some time in 1859, a similar experiment, attended by the same results, was also mentioned.

if we suppose a locomotive boiler to have 500 lbs. of its copper plates heated to 1,300 deg. (the melting point of copper being 2,160 deg.), this heat would be sufficient only to convert about 50 lbs. of water, already heated under the working pressure to 350 deg., into steam; the water being thrown up, we may suppose, by violent ebullition, as when the communication between the boiler and the steam-cylinder of the engine is suddenly opened. The total heat of steam is a little more than 1,200 deg., although its sensible temperature, to which the copper plates would be cooled in evaporating the water, is 414 deg. only at 275 lbs. pressure, which pressure would correspond very nearly with the density of 50 lbs. weight of steam when compressed into a steam-chamber of a capacity of 80 cubic feet, as in the larger class of locomotive boilers. And it must be understood that the whole quantity of disposable heat, as assumed above, must be appropriated by only 50 lbs. of water (assuming its temperature as 350 deg.),

in order that it may be converted entirely into steam. If this quantity of heat be distributed throughout a greater quantity of water, less than 50 lbs. of steam will be produced, inasmuch as a portion of the heat which would be necessary to produce it will have been absorbed in raising the temperature of the additional water, but without raising it into steam. It is plain enough that the quantity of heat which would be sufficient only to raise 50 lbs. of water into steam, would not suffice for converting any greater quantity of water, of the same temperature, into steam, and hence, with the quantities now assumed, 50 lbs. weight of steam could be produced only by the entire appropriation of the disposable heat, in the overheated plates, by 50 lbs. of water, and by the complete exclusion of this heat from any additional quantity of water admitted at the same time. If, therefore, the heat of 500 lbs. of copper plates at 1,300 deg. of temperature, were so far communicated to 50 lbs. of water of 350 deg. as to raise it

into steam of 275 lbs. pressure and 414 deg. temperature—the plates being cooled to the same temperature — the strain might, no doubt (added as it would be to the pressure of steam existing in the boiler before the admission of the water), burst it with all the violent effects of explosion. If, however, the situation of the overheated surfaces were such that a comparatively large quantity of cold water had to be admitted in order to cover a given area of hot metal, so that, by the time the 500 lbs. of copper were covered, 500 lbs. of cold water had been brought into contact with it, no steam could be formed, and the water would be raised by but about 100 deg. of temperature. Any considerable quantity of water being present, its circulation would be so rapid that the heat applied to it at the bottom would be almost instantly communicated throughout its whole mass. This deduction from the accepted laws of heat is borne out, experimentally, in plunging any weight of highly-heated metal into an equal

weight of cold water. After the metal has been cooled to the temperature of the water, little or no evaporation of the latter will be found to have taken place. A pint claret-bottle, the glass of which is by no means strong, may, when filled with cold water, be safely held in the hand whilst a red-hot poker, as large as can enter the neck of the bottle, is plunged into the water. Not only will there be no explosion, but after the poker has been cooled to the temperature of the water, the latter, when shaken up, will have hardly more than a blood-heat, and none of the water will be evaporated. If the hot iron be kept from actual contact with the glass, this simple experiment may be repeated at pleasure without even cracking the bottle.*

Much has been said of the spheroidal state of water when thrown upon heated plates. It would appear that, if ebullition were delayed in such case until after a considerable quantity of water had been admitted, the heat of the plate would be

* See Manual, p. 633, § 294; also § 279, as above.

so far absorbed in an equal or greater weight of water, that no explosion of the latter into steam could occur. This suggestion is given for what it is worth; but to my mind the spheroidal condition of water, under the circumstances mentioned, has long been an argument against, rather than in favor of, the probability of explosion.*

Superheated Steam. — When, however, the plates of a steam-boiler are burnt, the steam which may be in contact with them becomes superheated. Dr. Alban, in his work on the high-pressure engine, mentions that, in his practice, he often found tin-soldered joints in the steam-pipe melted by overheated steam. Jacob Perkins heated steam, out of contact with water, to extraordinary temperatures, and it was his theory that, steam being similarly superheated when the water in a boiler is low, the subsequent agitation of the water, from any cause, instantly pro-

* Manual, p. 582, § 282, for illustrations of violent explosive action certainly due this cause.—Ed.

duces a large additional quantity of steam, and sufficient to cause explosion. In regard to the degree to which steam may be superheated, Mr. Longridge has mentioned a case in his experience, a few years since, as Chief Inspector to the Manchester Boiler Association. In a boiler on which the steam-gauge marked a pressure of only 10 lbs. per square inch, the steam, held in contact with an overheated plate, became so highly superheated as to completely char the wooden lagging of the boiler, although the wood was entirely removed from any portion of the heating surfaces of the furnaces or flues. In a paper on the subject, read at the Institution of Civil Engineers in 1856, Perkins' theory of boiler explosions was reiterated at some length, and the writer (Mr. W. Kemble Hall) assumed that ordinary steam, superheated to say 435 deg., would instantly convert water, thrown among it, into steam of a pressure of 360 lbs. per square inch. The fact was overlooked, no doubt, that 75 cubic ft. of steam, at a pressure of

140 lbs. per square inch, weigh but 26 lbs., and that the specific heat of steam, at ordinary temperatures, is less than one-third that of water. Thus all the heat contained in 26 lbs. of steam, in a *loco*motive boiler, supposing the steam superheated even to 350 deg. above the temperature due to its pressure, could not generate much more than 3 lbs. of additional steam, which weight of steam, in the boiler in question, would not raise the pressure, at 140 lbs., to more than 160 lbs. to the square inch. Without pretending to any exactness in these figures, it is apparent upon a little consideration that the conversion of water into steam, by being thrown up in a divided state, into highly superheated steam, can hardly ever be sufficient of itself to account for any boiler explosion.* Dr. Alban has stated that in some of his experiments with a steam-generator, he

* In the Repertory of Patent Inventions, Supplement, January, 1832, page 424, Mr. Thomas Earle gave the results of a calculation similar to the above, and tending to disprove Perkins' theory, at that time being urged.

stopped the injection of water and kept the enclosed steam in contact with a metallic surface at a temperature of 800 deg., and yet no symptoms of an explosion appeared when the water was reintroduced. He adds that a long-continued injection was necessary before enough pressure could be obtained to set the engine at work again.

It is, nevertheless, a favorite opinion with many engineers that the presence of highly superheated steam within a boiler is sufficient to account for the most violent explosion. As compared with other current explanations of boiler explosions, it is perhaps no disadvantage to the explanation by superheated steam that it is incapable of proof. Although any one may blow up a boiler, no one has been able to prove, either by experiment or by calculation, that superheated steam, decomposed steam, or even electricity, could produce such a result. If, on the other hand, we proceed to investigate the properties of steam, under various conditions,

with such aids as science has placed at our disposal, we may satisfy ourselves that the explanations in question are erroneous ; and it is quite capable of proof by experiment that they are so. It is evident enough that no heat can be generated within the steam- or water-chamoer of a boiler. All the heat which may exist there must have been communicated from an external source—that is to say, from the fuel burning in the furnace. Heat acts by its quantity, just the same as ponderable matter ; and, so far as its effects are concerned, heat is as measurable as a solid body. If we cannot conceive the material existence of heat, we may observe, by the simplest experiment—that of plunging a hot poker into a pail of water—that a given weight of metal, heated to a given incandescence, will always impart a definite, and the same elevation of temperature to a given weight of the cooling or absorbing medium. The quantity of heat which will raise a pound of water through 1 deg. of temperature is as

definite and invariable as the quantity of water which will fill a given space, or as the weight, at any height of the barometer, of the air we breathe.

No one, perhaps, would deny these well-known truths in the abstract, and I must plead, as my excuse for repeating them, the general oversight of such facts in the explanation of boiler explosions by superheated steam. Although the sum of the sensible and latent heat of ordinary steam is not constant at all pressures, it is nearly so. Practically, steam not superheated cannot lose any part of its heat without being more or less condensed. In other words, it cannot make an additional quantity of steam; since, to do so, it would require to possess the power of producing and communicating an amount of heat which it did not previously contain. Steam may be led from one vessel and made to boil water in another, but this is only a transference of steam, as all the steam formed in the second vessel will disappear from the first, and as much more

besides as was required to raise the water in the second to the boiling point. With ordinary steam, the injection of any quantity of water, cooler than itself, among it, is attended with a partial condensation of the steam, and the elevation of the temperature of the water, but never by the production of additional steam. The quantity of heat which will raise 1 lb. of water through 1 deg. being termed an "unit of heat," about 1,150 units will be required to convert 1 lb. of water, at 60 deg., into steam. But if the heat for conversion come from superheated steam (and it must be superheated, in order to generate additional steam, since it can part with none of its ordinary or normal heat without more or less conpensation), we then find that, owing to the difference between the specific heat of steam and that of water, a pound of the former must be superheated by nearly 3,500 deg., in order to impart 1,150 units of heat to a pound of the latter ; at the same time maintaining its own existence as steam. Consid-

ering that an ordinary locomotive boiler seldom contains 25 lbs. of steam, disengaged from the water, and that even 1,000 deg. of superheating in addition to from 300 deg. to 350 deg., the ordinary temperature of the steam, would be excessive, the explanation by superheated steam appears sufficiently incomplete to warrant its rejection.

The foregoing reasoning upon the production of steam from water thrown upon red-hot plates was first suggested to me by Mr. D. K. Clark; although I understand Mr. Clark to hold the opinion that the steam thus produced cannot be sufficient to account for boiler explosions. Under certain circumstances, I believe a boiler may be violently exploded by the steam thus formed, and I think the explanation by overheating possesses considerable probability, although it cannot, of course, be adopted in those frequent cases where there is proof that no overheating has taken place.*

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* Manual, p. 559, §§ 275–276; in which are described the corroboratory experimental work of Lawson.—Ed.

Electricity.—The well-known fact that steam sometimes exhibits electrical properties on being discharged into the air, no doubt suggested the electrical hypothesis of boiler explosions. Those, however, who have adopted this hypothesis are unable to furnish any evidence of the existence of free electricity within a steam-boiler. All our knowledge of electricity goes to show that even if it were developed by ebullition, or in steam when confined under pressure, it could not collect within a metallic vessel, which, like a boiler, is in perfect electrical communication with the earth. The electrical phenomena sometimes observed when steam is being discharged into the air are believed to be caused partly by the friction of the escaping steam upon the inner surfaces of the discharging channel; whilst it is possible that electricity is also liberated in the condensation of steam in the open air.

Professor Faraday has examined with great care the action of Armstrong's

hydro-electric engine,* in which steam, generated from distilled water in a boiler insulated upon glass supports, produces electricity on being discharged through a peculiar apparatus into the air. The steam is led by a pipe from the boiler, and through three or more small passages surrounded with a cooling apparatus, by which the steam is partially condensed into drops of water. In this state it enters, by tortuous passages, a series of discharging nozzles, each of which has an internal bushing or lining of box-wood. On the final discharge of the steam from these nozzles into the air, electricity is disengaged, and is collected by suitable metallic points connected with an ordinary conductor. Although powerful discharges can be thus obtained, there is no evidence whatever of the presence of electricity within the boiler. Indeed it is only by certain

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* The hydro-electric engine in the "Conservatoire des Arts et Métiers," at Paris, is the only one of the kind that I have seen, and I have taken the results of Professor Faraday's examination of the machine from Gavarret's "Traité d'Electricité," Paris, 1857.—Z. C.

very peculiar arrangements that electricity is obtained at all. Professor Faraday found that if, instead of distilled water, ordinary spring water, containing the usual proportion of atmospheric air, was employed ; or, if any saline, acid, or alkaline substance capable of acting as a conductor, was dissolved in the water in the boiler, there was no electricity to be had. Nor did the conductor become charged unless the process of partial condensation was maintained in the "refrigerating box ;" and, what was more singular, nothing but *box-wood* nozzles appeared to have the power of finally exciting the electrical action at the instant of discharge.

The results of Professor Faraday's researches, as to the mode in which electricity was produced in the experiments which he made with Armstrong's machine, comprise the following facts:—

1. The production of electricity is not due to any change in the state of the liquid contained in the boiler.

2. A current of dry steam produces no

development of electricity. The production of electricity is due to the friction in the box-wood nozzle of the drops of water, formed by the partial condensation of the steam in the refrigerating box.

3. Increasing the pressure of the steam increased the development of electricity by increasing the friction of the issuing jets of steam and water.

4. The same results were obtained from compressed air, discharged through the box-wood nozzles, as from steam discharged under the same circumstances. When the air was perfectly dry there was no development of electricity; when the air was humid, and contained besides a very little pulverulent matter, the friction of discharge produced electricity in the same manner as when steam was employed in the experiments.

It will be borne in mind that with all the special and peculiar conditions requisite for the production of electricity by this apparatus, the boiler must be perfectly insulated on glass supports. And

although Mr. Armstrong probably constructed his machine under the impression that the generation of steam was essential to the results sought to be obtained, Professor Faraday found that the same results were disclosed when atmospheric air, condensed to the same pressure as the steam, was employed in its stead.

It has been ingeniously argued that steam-boilers may become insulated by an internal coating of boiler-scale. It would be necessary, however, that this scale should completely cover every part of the internal surfaces of the boiler, and even those of the steam-pipe, stopcock, etc. A single crack in any part of this complete dielectric lining would liberate any electricity which might be contained in the steam. Whilst there is no probability that any steam-boiler was ever so completely lined with scale, there is another fact which appears to dispose of the electrical explanation, even if perfect insulation existed. This fact is, that water may be boiled in a perfect

Leyden arrangement with no development of electricity.

Without pursuing the electrical hypothesis any further, we may observe that no one has yet offered to explain how electricity, even if it existed in high tension, would explode a steam-boiler. And, if it exist at all in steam-boilers, why does it not exist in all boilers? And if in all, why does it not manifest its presence in other ways than in explosions? If electricity act at all it must be by quantity, and if the quantity developed be sometimes sufficient to burst boilers, we have a right to look for visible, although milder, phenomena when the quantity is insufficient. Yet no phenomena of the kind, sufficient to excite alarm, or even to attract attention, are observed. The fact is, no one has elaborated the electrical hypothesis into anything like a theory of boiler explosions. The presence of electricity has been suggested, and among those who prefer mystery, or, at least, very obscure explanations, to circumstantial investigation,

some have referred boiler explosions to electricity.

Decomposed Steam.—The unsatisfactory results generally obtained by those who have sought to decompose water by heat, on a large scale, with the view of applying its elementary gases separately, does not ap~ear to have prevented the occasional adoption of the hypothesis that, in certain cases, all the steam contained within a boiler is decomposed, and its hydrogen (by some means not easily explained) exploded with great violence. That steam, passed over pure metallic iron heated to redness, is decomposed is perfectly true, although the iron must retain all the oxygen separated in the operation. With oxidized iron, however, the process of decomposition cannot be continued. This is, I believe, a chemical fact of which there can be no dispute. To decompose 1 lb. of water (or steam, which is chemically the same substance), 14.2 oz. of oxygen must be fixed by the iron, and only 1.8 oz. of hydrogen' will be set free. This large

proportion of oxygen, absorbed by only a few square feet of overheated surfaces, would soon form an oxide of iron of sufficient thickness to arrest all further decomposition, and all the hydrogen up to that time disengaged would not amount, perhaps, to 1 lb. in weight. By itself, or mixed with steam, hydrogen cannot be exploded, nor even ignited. It will extinguish flame as effectually as would water.

Upon this subject, I may refer to a report made by Professor Faraday in May, 1859, to the Board of Trade, upon the liability to accident consequent upon the introduction of an apparatus for superheating steam on board the Woolwich steamboats. In this apparatus the steam was carried, in iron pipes, immediately through the furnace and in contact with the incandescent fuel. Professor Faraday, after having examined the apparatus at work, says:—

"I am of opinion that all is safe, *i.e.*, that as respects the decomposition of the steam by the heated iron of the tube, and

the separation of hydrogen, no new danger is incurred. Under extreme circumstances the hydrogen which could be evolved would be very small in quantity—would not exert greater expansive force than the steam—would not with steam form an explosive mixture—would not be able to burn with explosion, and probably not at all if it, with the steam, escaped through an aperture into the air, or even into the fire-place.

"Supposing the tubes were frequently heated over-much, a slow oxidation of the iron might continue to go on within; this would be accompanied by a more rapid oxidation of the exterior iron surface, and the two causes would combine to the gradual injury of the tube. But that would be an effect coming under the cognizance of the engineer, and would require repair in the ordinary way. I do not consider even this action likely to occur in any serious degree. I examined a tube which had been used many months which did not show the effect; and no

harm or danger to the public could happen from such a cause."

Professor Taylor, of Guy's Hospital, reported in part, as follows, upon the same apparatus:—

"It is true that steam passed over pure metallic iron heated to redness (1,000 deg.), is so decomposed that the oxygen is fixed by the iron while hydrogen gas is liberated. This chemical action, however, is of a very limited kind. The surface of the iron is rapidly covered with a fixed and impermeable layer of the magnetic oxide of iron, and thenceforth the chemical action is completely arrested. If the interior of an iron pipe has been already oxidized, by passing through it, while in a heated state, a current of air, there will be no decomposition of steam during its passage through it. If the interior of an iron pipe were not thus previously oxidized, it would speedily become so by the oxygen derived from the air, which is always mixed with steam. Hence, chemically speaking, under no circumstances, in my opinion,

would any danger attend the process of superheating steam, as it is conducted under this patent.

"It is proper also to state, that hydrogen is not explosive, but simply combustible, and assuming that it was liberated as a result of the decomposition of superheated steam, its property of combustibility would not be manifested in the midst of the enormous quantity of aqueous vapor liberated with it and condensed around it. There could be no explosion, inasmuch as hydrogen, unless previously mixed with oxygen, does not explode; and oxygen is not liberated; but actually fixed by the iron in this process. It is a demonstrable fact that the vapor and gas evolved under the form of superheated steam, tend to extinguish flame and to prevent combustion from any other cause."

Professor Brande, in a report made by him to the patentees of the same apparatus, observes:—

"In reference to the question which you have submitted to me, respecting the

possible or probable evolution of hydrogen gas and consequent risk of explosion in the processes and by means of the apparatus which you employ for the production of superheated steam, I am of opinion that there can be no danger from such effect; that the temperature to which the iron pipes connected with your boiler are raised, and the extent of the iron surface over which the steam passes, are insufficient for its decomposition; and that if the temperature of the pipes were even raised considerably beyond that which you employ, or would be able to attain, a superficial layer of oxide of iron would line the interior of the heated pipes, and so prevent any continuous decomposition of water. Effectually to decompose steam, by passing it over iron, it is necessary that a very extended surface of the metal (as in the form of thin plates or iron turnings) should be used, and that the temperature should be continuously maintained at a bright red heat, namely at a temperature considerably above 1,000 deg. of Fahrenheit.

"I have read Dr. Taylor's report, and entirely agree with the inferences he has drawn as to the absence of danger from the evolution of hydrogen gas in practically carrying out your process for the production and application of superheated steam."

The practical conclusions upon this subject are the following:—1. Decomposition cannot possibly occur, to any considerable extent, under any circumstances arising in the working of ordinary steam-boilers; 2, If it did occur, the hydrogen thus liberated would have no access to oxygen, without which it could neither inflame nor explode; 3, Even if oxygen were present, the presence of steam would prevent ignition; and, 4, If oxygen were present, and no steam existed in the boiler, the hydrogen would only inflame and burn silently as fast as it was produced, the heat for ignition being supposed to come from a red-hot plate. Under these accumulated impossibilities of violent explosive action, the explanation of boiler explosions by the decompo-

sition of steam is without any support whatever.

Overpressure.—Any pressure, whether gradually or momentarily generated in a boiler, is an overpressure when it exceeds the safe working pressure; and, strictly speaking, there must always be overpressure whenever a boiler is burst. When, however, an explosion is said to have occurred by overpressure, it is commonly understood that the pressure has been allowed to increase gradually up to the limit of the strength of the boiler, and if this has been calculated to correspond to a pressure of 700 lbs., for instance per square inch, the actual pressure at the moment of explosion is accordingly assumed at that moment. Boilers may, perhaps, be generally capable of withstanding nearly their full calculated bursting pressures; indeed, comparatively few boilers do fail in any way, for after all, the number of explosions—numerous as they are—bears but a very small proportion to the actual number of boilers in use. But for the purposes of investi-

gation, there are abundant instances of the quiet rupture of steam-boilers under ordinary working pressures, so that even a violent explosion does not absolutely prove that the pressure under which it occurred was anything like the calculated bursting pressure of the boiler. If the bursting pressure be 758 lbs. per square inch it might not be difficult to raise the steam to that point and burst the boiler. Yet it is very improbable that anything like a pressure of 758 lbs. per square inch ever accumulates in a boiler intended to work at 100 lbs. or 125 lbs. We will suppose a locomotive boiler with 75 cubic ft. of water-room containing 4,650 lbs. of water, and 75 cubic ft. of steam-room containing 23 lbs. in weight of steam at a pressure of 120 lbs. per square inch. To increase the pressure even to 285 lbs. per square inch, $25\frac{2}{3}$ lbs. additional weight of steam would have to be compressed into the steam-chamber, and the remaining $4,624\frac{1}{3}$ lbs. of water would have to be raised to 350 deg., the temperature of steam of 120 lbs. to $417\frac{1}{2}$ deg., the tem-

perature of steam of 285 lbs. pressure. The $25\frac{2}{3}$ lbs. of additional steam, formed from water of an average temperature of 380 deg., would have absorbed about 21,000 units of heat, whilst the elevation of the temperature of 4,624 lbs. of water, by $67\frac{1}{2}$ deg., would require 312,120 units of heat. The whole heat thus expended would equal that necessary for the evaporation of about 285 lbs. of water under a moderate pressure, and this heat would require the combustion of at least 32 lbs. of good coke. Although the steam-gauge of a locomotive will often rise 7 lbs. or 8 lbs. a minute in standing, and 10 lbs. or even 15 lbs. when a strong blast is turned up the chimney when running with a light load, the steam could not probably rise from 120 lbs. to 285 lbs. in much less than twenty minutes under any circumstances likely to occur in practice. Mr. Fairbairn has calculated that with a certain locomotive boiler on which he experimented, 43 minutes would be required to raise the pressure from that of the atmosphere to 240 lbs. With the

same boiler under the same circumstances as in the first experiment, 28 minutes would be required to raise the pressure from 60 lbs. to 300 lbs. per square inch. The rapidity with which the steam-pressure would rise would altogether depend upon the relative extent and temperature of the heating surface to the quantity of water in contact with it. Mr. Martin Benson, who has had much experience in the working of the steam fire-engines employed at Cincinnati, United States, informs me that, with the fires carefully laid with light combustible materials, steam has been raised in the boilers of these engines in 4 min. 38 sec., from cold water to a pressure of 65 lbs. per sq. in. In 2 min. the pressure has been raised from 10 lbs. to 90 lbs. per sq. in. In these boilers, however, the tubes are first heated, and small quantities of water are afterwards injected into them, the whole quantity of water at any time in the boiler rarely exceeding one cubic foot.*

*Manual, p. 589, § 283; exhibiting the fact of such

The simple increase of pressure in a boiler, either when at work or when standing, must undoubtedly be comparatively gradual—a matter of some minutes, at least. Whatever might cause the steam-gauge to mount, suddenly, from 100 lbs. to the limit to which it is marked, it is very certain that the necessarily gradual increase of the heat of the water within the boiler could not produce such a result. Yet those who have given any attention to the subject of boiler-explosions are aware that they frequently occur when, without any overheating of the plates, the pressure stood, but a moment before, at the ordinary working point. In the case of the locomotive boiler which exploded in the summer of 1858, at Messrs. Sharp, Stewart & Co.'s, at Manchester, the pressure, as observed upon two spring balances and a pressure-gauge, stood at 117 lbs. to 118 lbs., a minute before the explosion, both valves blowing off freely at the time. The part of the boiler which

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explosions occurring, and presenting the computations.
—Ed.

exploded was the ring of plates next the smoke-box, out of the influence of any part of the fire. The fact, therefore, of the violent explosion of a strongly made boiler at 117 lbs., is a proof that it is not necessary to assume and to account for the existence of any pressure about that point. On the 5th of May, 1851, a locomotive engine, only just finished, burst its boiler in the workshop of Messrs. Rogers, Ketchum & Grosvenor, at Paterson, New Jersey, United States. I was upon the spot but a few moments afterwards, and found the effects of the explosion to be of the most frightful character: a considerable portion of the three-story workshop being blown down, whilst four men were instantly killed, and a number of others were injured, one of whom died soon afterwards. Several of the men, who, although immediately about the engine at the time, escaped unhurt, unanimously declared that the safety-valves were blowing off before the explosion, and that the two spring balances indicated, but a moment before

the crash, a pressure of but 110 lbs. per sq. in. On the 12th of February, 1856, the locomotive Wauregan exploded, after standing for upwards of two hours in the engine-house of the Hartford, Providence, and Fishkill Railroad, at Providence, United States. Only sufficient steam had been maintained in the boiler to enable the engine to be run out of the house; but at the time of the explosion the engine had not been started, the engine-man, who was killed, being upon the floor, at the side of the engine, at the time. The boiler gave out in the ring of plates next behind the smoke-box.* Destructive explosions often occur at pressures of 10 lbs. to 12 lbs. per sq. in. in low-pressure boilers; and it is on many accounts improbable that anything like the calculated bursting pressures of boilers is ever reached, even where the most frightful explosions have occurred. Not only would the accumulation of steam of the calculated bursting pressure require considerable time, but

* Manual, § 281, p. 581, for account of this case.—Ed.

the gauge, if there were one, would soon be fixed at the limit of its motion, and the safety-valves, if they were not wedged down, would blow off with unusual violence. In the case of locomotive engines, which have no self-acting governors, any considerable increase of pressure would, if the engine were under way, quicken its speed, and cause the driving-wheels to slip upon the rails to such an extent as to arrest the attention of the engine-man. The fact that he would have to nearly close the regulator, and keep it nearly closed, whilst drawing a load with which it was at other times necessary to run with the regulator wide open, would be a significant indication of the state of things in the boiler.

If boilers burst only from overpressure, they would, of course, give out first—as, indeed, they always must—in the weakest part; say, along a seam of rivets, which is but about one half as strong as the solid plate. But, after one seam had opened, the relief of pressure would be so instantaneous that, without subse-

quent percussive action, the rupture could hardly extend itself through solid plates of nearly twice, or even, perhaps, ten times the strength of the part which first gave way. The general strength of the solid plates of a boiler should be, and probably is, from ten to twenty times greater than that of any part so weak as to rupture, as is often the case, under the ordinary working pressure. Mr. Whitworth has made an experiment upon one of his new cannon, made of homogeneous iron, which shows how a great pressure may relieve itself by a very small opening. After loading one of his 3-pounders, he plugged the muzzle so as to render it impossible for the gun to discharge itself in the ordinary manner. On firing the charge the piece did not burst, but all the gases escaped through the "touch-hole." This severe test was repeated several times. In the case of excessive pressure, there would be many circumstances to attract the attention of the attendants, whereas explosions more

commonly occur with little or no warning whatever.

This line of argument tends, undoubtedly, to assimilate the conditions of violent explosion to those of quiet rupture; and although like causes should produce like effects, it may perhaps be shown that, so far as pressure alone is concerned, either explosion or simple rupture may occur indifferently at one and the same actual pressure, existing up to the moment of failure. Instead, therefore, of calculating the strength of a boiler from its diameter and the thickness of the plates, and then assuming that it can only burst at a corresponding pressure, I shall adopt the fact of quiet or simple ruptures as proving (what might, indeed, be taken for granted) that boilers are not always as strong as they are calculated to be; and I shall then endeavor to show how violent explosion may result in one case from a pressure which only causes quiet rupture in another.

Strength of Heated Iron.—Overheat-

ing, which has been considered with reference only to the generation of steam from water suddenly thrown on heated plates, and with reference to the decomposition of steam, may materially reduce the strength of boiler-plates. Up to temperatures of 400 deg. and 550 deg. boiler-plates have not been found to be weakened; indeed, the experiments of the Committee of the Franklin Institute indicated a gradual gain of strength, with increasing temperatures, up to a certain point, and that the strength at 550 deg. was equal to that at 55 deg. Mr. Fairbairn finds the strength diminished one-fourth at a red heat; and it is not difficult to understand that, at a very high heat, no reliance whatever could be placed upon iron or copper when subjected to strain.* The furnace-flues of Cornish boilers, and the crown-plates of locomotive boilers, frequently alter their shape when overheated, and are often continued in regular work, until from

* Manual, p. 568; § 278, and for detailed account of loss of strength by heat, especially, p. 83, § 37.—Ed.

some cause—another burning, perhaps—they give out entirely. Although an examination of the furnace-plates, recovered from an explosion, often shows that they have never been subjected to an injurious temperature, overheating must be taken as one among the various causes which may operate to weaken a steam-boiler.

Tests by Pressure.—Again, as it is considered injurious to a boiler to prove its strength, before it is put under steam, by a great hydrostatic pressure, we have no better means of ascertaining its actual strength than by inferring the bursting pressure from its dimensions, and from the thickness and general quality of the plates. Indeed, the actual strength of a boiler can be ascertained only by a process which involves its destruction. In other words, pressure of some kind must be accumulated within it until it bursts, in order to know what amount of pressure will suffice to burst it. A new locomotive boiler, of peculiar construction, which exploded in Octo-

ber, 1856, at Messrs. Bolckow & Vaughan's ironworks, at Middlesborough-on-Tees, was believed to have been injured in a previous test, by steam-pressure of 130 lbs. per sq. in.* Dr. Joule, of Manchester, has lately called attention to the liability to injury to which boilers are exposed under tests by steam or hydrostatic pressure. He proposes a test employed by himself with entire success for the last two years. He fills the boiler entirely full of water, and then makes a brisk fire upon the grate. When the water has been warmed to from 70 deg. to 90 deg., the safety-valve is loaded to the pressure up to which the boiler is to be tested. The rise of pressure is then carefully observed by a steam-pressure gauge; and if the progress of the pointer be constant and uniform, without stoppage or retardation, up to the testing pressure, it is inferred that the boiler has withstood it without strain or incipient rupture. In this mode of testing,

* See Manual, p. 601, § 287, for illustration in case of the "Westfield."—Ed.

the expansion of the water, by heat, is so rapid, that Dr. Joule has found the pressure to rise from zero to 62 lbs. per sq. in. in five minutes. But this mode of testing the strength of a boiler cannot, any more than any other mode, show the strength beyond the testing pressure; it cannot show the actual strength or bursting pressure of the boiler except that be destroyed in the test. And although the quality of the materials and workmanship in steam-boilers may vary generally within narrow limits only, not only different boilers, but different parts also of the same boiler, are of very unequal strength. The weakest part of the weakest boiler may be almost immeasurably weaker than the strongest part of the strongest boiler. The material of which boilers are made varies greatly in strength. In Messrs. R. Napier & Sons' recent experiments (conducted by Mr. David Kirkaldy) upon the strength of iron and steel, one sample of Farnley plate iron bore a strain of 62,544 lbs. per sq. in.,

whilst another sample of iron from the same makers broke under a strain of 40,541 lbs. per sq. in. Glasgow ship-plates bore, in one case, 53,370 lbs. per sq. in. and in another only 32,440 lbs. Even Lowmoor iron varied in strength between the limits of 47,426 lbs. and 57,881 lbs. per sq. in. However the strength of iron may be averaged for the general purposes of the engineer, we are never justified in assuming an average or standard strength for the particular parts of a steam-boiler which, in the case of explosion, were the first to give out. The fact of explosion is in itself *prima facie* evidence that these parts were not of average strength, and affords good ground for the presumption that they were of only the minimum strength; and the minimum strength of iron is not known, for however weak a given specimen might be, another one, much weaker, might doubtless be found. Comparatively, few experiments have ever been made upon the strength of plates, and the averages given by Mr.

Fairbairn and others have been taken from comparatively few trials. Messrs. Napier's experiments were considered very comprehensive; yet they included only 150 specimens of iron plates, with which number the range of strength was from 32,450 lbs. to 62,544 lbs. per square inch. Mr. Fairbairn found the strength of a broken plate, taken from the boiler which exploded at Messrs. Sharp, Stewart & Co.'s, to be only 4.66 tons per square inch, or but one-fifth of the proper average. It is presumable, perhaps, that the strength of plate iron varies within as wide limits as that of cast iron, from which plate iron is made, and upon the quality of which its own must also depend. The Government cast-iron experiments concluded last summer, at Woolwich, comprised 850 specimens, ranging in strength from 9,417 lbs. to 34,279 lbs. per square inch, the average strength of all the specimens being 23,257 lbs. It must be remembered, however, that the sample which bore only 9,417 lbs. per square inch cannot be taken as the weak-

est which would occur in practice, inasmuch as it was not selected at random from iron in the market, but was one of several samples which had been contributed by a long-established firm, with the expectation, no doubt, of obtaining the preference of the authorities. If the poorest iron were purposely sought for, as it should be, in order to estimate the chances of failure, cast iron could, no doubt, be found which would not bear a strain of 3,000 lbs. per square inch; whilst, on the other hand, there are authenticated instances of tests in which cast iron did not yield until the strain had reached 45,000 lbs. per square inch.

Apart, also, from the quality of the iron, its thickness varies greatly in the practice of various makers. In the United States, for example, the plates in the waist of a locomotive boiler, 48 in. in diameter, and intended to carry steam of 120 lbs. per square inch (sometimes increased to 160 lbs. or more), are $\frac{1}{4}$ in. only, although $\frac{5}{16}$ in. plates are occasionally used. In England, the thickness of

plates for such a boiler is from $\frac{3}{8}$ in. to $\frac{1}{2}$ in.; $\frac{7}{16}$ in. being a common thickness. In France a 48-in. locomotive boiler, the pressure within which rarely exceeds 120 lbs., is generally 15 millimetres, or $\frac{6}{10}$ in. thick. The strongest form of a boiler is a homogeneous metal tube, drawn solid, and of from say $1\frac{1}{2}$ in. to 2 in. diameter. Its bursting pressure is seldom less than 7,000 lbs. per square inch; in some cases, as much as 15,000 lbs.

In working iron into steam-boilers, it is commonly supposed that the loss of strength in punching is proportional only to the width punched out. If, in a row of rivet holes, in the edge of a plate 24 in. wide, there are 13 holes of $\frac{3}{4}$ in. diameter, the length of iron removed in the line of strain is $13 \times \frac{3}{4} = 9\frac{3}{4}$ sq. in., or but about two-fifths of the whole width of the plate. Mr. Fairbairn has found, however, that the strength of a given section of plate iron, as left, after punching, between two rivet holes, is actually less than the strength of an equal section of the same plate before

punching. In eight experiments, the highest strength of the plate experimented upon was 61,579 lbs., and the lowest 43,805 lbs., per sq. in., the average of the whole being 52,486 lbs. per sq. in. But with the same plate, after punching, the strength per square inch of the metal left between the holes varied between only 45,743 lbs. and 36,606 lbs., the average of seven tests giving only 41,590 lbs. per sq. in. of the remaining solid iron, against 52,486 lbs., the strength of the same section of the same iron before punching. With this injury, therefore, in punching the iron, by which even the remaining solid iron is weakened by more than one-fifth, the strength of an ordinary single riveted seam is, as was many years ago ascertained by Mr. Fairbairn, only 56 per cent., or a little more than one-half that of the same plate tested through solid iron away from the seam. Single riveting alone, therefore, destroys, upon the average, 44 per cent. of the strength of the weakest plate

worked into a steam-boiler.* In some cases, the injury by punching may be much greater than was apparent in Mr. Fairbairn's experiments. I have seen, in one of the most extensive engine works in France, punched plates of iron, $\frac{6}{10}$ths in. thick, in which there were cracks from three consecutive rivet holes to the outer edge of the plate.† As sometimes made up (and in dealing with boiler-explosions it is our business to look for extreme cases), the plates are got together by the aid of "drifts," and the iron is under a greater or less initial strain before steam is ever raised in the boiler.

Apart from the quality of the materials, and from the effects resulting from the ordinary processes of securing them together, the general construction of a steam-boiler greatly affects its strength. In Mr. Fairbairn's experiments upon the stayed sides of locomotive fire-boxes, a plate-iron box, made to represent the side of a strongly stayed fire-box, bore, in one

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* Manual, p. 117, § 50.—Ed.

† Ibid. p. 123, § 51.—Ed.

case, the enormous pressure of 1,625 lbs. per sq. in. before yielding. The strength of the sides of a locomotive fire-box depends, however, almost entirely upon the stay-bolts alone, as without these the sides of the fire-box would be the weakest parts of the whole boiler. Yet I have frequently found these stays (where made of wrought iron) to be as brittle, after a few years' use, as coarse cast iron. I have broken them off from the sides of old fire-boxes, sometimes with a blow no harder than would be required to crack a peach-stone. The upper stay-bolts appear to suffer the most. Their deterioration, after long use, has been attributed to slight but repeated bendings, caused by the expansion of the fire-box every time the fire is lighted, and its subsequent contraction when the boiler is again cooled. Upon this supposition, some locomotive makers turn these bolts to a smaller diameter in the middle of their lengths than at their ends, with the view of permitting a "spring" without

short bending, under the alternating movements of the fire-box.

Mr. Fairbairn's experiments upon the strength of iron tubes have, as is well known, disclosed most important facts bearing upon their relative resistance to internal and external pressure. Until the recent announcement of Mr. Fairbairn's discovery that the resistance of metal tubes to collapse was, within certain limits, inversely as their length, their strength, or, more properly speaking, their weakness, was generally unknown. One startling result, as ascertained from the experiments under notice, was, that, whilst the bursting pressure of a boiler 7 ft. in diameter, 30 ft. long, and composed of single-riveted $\frac{3}{8}$ in. plates, of average quality, was 303 lbs. per sq. in., the collapsing pressure of its 3-ft. internal plain flue of the same thickness of metal, was but little more than 87 lbs. per sq. in., or hardly more than one-fourth that required to burst the shell.*

* Manual, p. 140, § 56.

Defects of Construction.—The steam domes of locomotive boilers are sometimes of more than one-half the diameter of the barrel, which is consequently much weakened.* It has been observed that locomotive boilers frequently burst through the plates to which the dome is attached, or through the plates immediately adjoining. Locomotive boilers, also, are occasionally, though not often, made of an oval section, their vertical diameter being 3 in. or 4 in. larger than the horizonal diameter. A large number of the locomotives constructed by the late M. Camille Polonceau, at the Ivry workshops of the Paris and Orleans Railway, have oval boilers of this kind. Although such boilers are unquestionably weaker than when made of a truly cylindrical form, there are very few explosions upon the Orleans, or indeed upon any of the French lines. An engine exploded some two years ago at the Corbeil Station of the Orleans Railway.

The employment of angle-iron in the

* Manual, p. 593, § 285.

construction of many of the older locomotive boilers involved some danger, and it is doubtful if the real resistance of angle-iron to longitudinal cracking is known at all. In Messrs. Napier's experiments, last summer, four bars of Consett ship angle-iron bore from 43,037 lbs. to 54,962 lbs. per sq. in. when broken by a strain in the direction of their length. The process of manufacturing angle-iron tries it most severely, however (unless the iron be originally of the very best quality), by inducing incipient cracking along its length, giving it a reedy structure, and thus inviting the complete separation of one leaf from the other at the bend. Not a pound of angle-iron has been employed for several years in the construction of American locomotive boilers, and as far as I am aware the French locomotive makers have abandoned its use. All the angular junctions in the outer shells of American locomotive boilers are rounded with an easy curve of seldom less than 4 in. radius. The square corners made in the inside fire-box plates,

which are almost always of iron, require the very best quality of metal of a thickness of not more than $\frac{5}{16}$ in., whilst the usual thickness is only $\frac{1}{4}$ in. I have frequently seen what was considered to be a good quality of $\frac{3}{8}$ in. plate cracked completely in two under the attempt to bend it to a square corner.

The defects originally existing in a plate of iron are occasionally discovered after its failure has produced a violent explosion. The freight engine Vulcan, employed upon the Buffalo and Erie Railroad, U. S., burst its boiler with terrific violence in August, 1856. Although the engine was one of three which had been built, as was believed with unusual care, one of the broken plates, afterwards recovered, exhibited a flaw 24 in. long. The plate which first gave way formed a part of the outer fire-box and extended to the dome, the 24 in. opening for which was an additional abstraction from the strength of the structure. The upper part of the fire-box was blown completely off to one side, and the engine

was thrown, bodily, 25 ft. to the other side, and into a ditch.

The case of the engine Vulcan illustrates that of many others where explosions have occurred in consequence of a congenital defect, after the boiler had been for a considerable time at work. It would be natural to ask why, if a boiler be originally defective, it does not explode the first time it is brought under steam? How can the final explosion be delayed one, two, or even ten years, when, all along, a hidden flaw, a broken rivet, or a rotten plate existed in the boiler; and whilst explosion, therefore, must have been constantly impending under an almost perfect equilibrium between strain and resistance? Does the strength of the boiler, after it has been completed, deteriorate rapidly by use? Mr. William Shaw, Jr., of the Tow-lane Ironworks, Durham, wrote to "The Engineer" newspaper, under date of 15th December, 1856, stating that, whilst he had 20 high-pressure boilers under his inspection, he had found fibrous iron, after a few years'

use, to become crystallized, and as brittle as blister steel. On the other hand, Mr. Samuel J. Hayes, formerly Master of Machinery of the Baltimore and Ohio Railroad, U. S., and now holding a similar appointment upon the Illinois Central Railroad, at Chicago, Ill., U. S., has informed me that he tested some of the plates of a boiler which exploded at Baltimore, in 1852, after 15 years' service, and that the iron bore an average tensile strain of 60,000 lbs. per sq. in. before yielding. It is doubtful if the iron in a steam-boiler alters its condition except by over-heating; although certain parts of the boiler may sustain injury from alternate expansion and contraction. Mr. Frederick Braithwaite read a paper, some time ago, before the Institution of Civil Engineers, upon the "Fatigue of Metals," in which paper iron was assume to lose its strength under long continued strain. I cannot enter here upon the conclusions of the paper in question, but I may refer to an experiment, made, I believe, by Mr. Fairbairn, wherein a cast-iron column was

loaded with .97 of its estimated breaking weight, which weight was supported for six months, when the column broke.* It is evident enough that a steam-boiler, especially a locomotive boiler, is exposed to constant influences tending to weaken it; and, apart from all reasoning under this head, the fact of the frequent quiet rupture of steam-boilers, sometimes after several years' steady work, is a sufficient proof that local defects, whether original or produced, may exist for a long time before the actual failure of the defective parts.

Defects of Materials.—With regard generally to failures resulting from an inferior quality of materials or workmanship, or from improper construction or management, it may be said that whereas but one explosion occurred in the year 1859, among the 1,618 boilers under the care of the Manchester Boiler Association, no less than 14 boilers were found to be in a "dangerous" condition, and 100 in an "unsatisfactory" condition from the frac-

* Manual, p. 74, § 35,—conclusive evidence on this point.

ture of plates ; at least one boiler out of every fifteen under inspection having exhibited an injury of that kind in a single year. But for the admirable system of boiler-inspection pursued in Manchester (and more recently adopted at Huddersfield), the larger number of these injuries would have remained undiscovered, and instead of one explosion there might have been twenty.

Corrosion sometimes goes on entirely unsuspected. In a boiler which recently exploded at Tipton, considerable breadths of the iron were found to have been reduced in thickness to $\frac{1}{64}$ in. In the case of the explosion of a boiler at the Clyde grain mills, at Glasgow, in April, 1856, extensive breadths of the iron were said to have been reduced to the thickness of a sixpence; and in the disastrous explosion which occurred in August of the same year, at Messrs. Warburton & Holker's, at Bury, the evidence showed that the bottom plates had been reduced for a greater or less width to only $\frac{1}{10}$ in. in thickness. In the year 1859 there were

reported 44 cases of "dangerous," and 153 cases of "unsatisfactory" corrosion, among the 1,618 boilers under the inspection of the Manchester Boiler Association. Thus there was nearly one case of corrosion in every eight boilers, in a single year.

All these facts, it will be observed, support the probability of explosion at nearly the ordinary working pressures. And, in the majority of cases, I believe it may be correctly assumed, in the absence of positive evidence to the contrary, that an exploded boiler, although to all appearance perfect up to the moment of rupture, contained some hidden defect. The fact of explosion, except under very peculiar circumstances, appears to be a better evidence of a defect in the boiler than of the previous existence of anything like a calculated bursting pressure of steam; such as 500 lbs. or 600 lbs. in a boiler made to work at 100 lbs. per sq. in.*

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* Manual, p. 642, § 295. This point is probably now beyond question.—Ed.

If, however, boilers of the full calculated strength have ever been burst by gradually accumulated pressure, it would be the easiest thing possible to prevent the recurrence of such disasters. If one one or two safety-valves are sufficient, under ordinary circumstances, to liberate the steam as fast as it may be generated in the boiler, three, four, or, certainly, half-a-dozen equally large safety-valves, all blowing off at just above the ordinary working pressure, and all acting independently of each other, would effectually prevent all chance of overpressure. If the explanation by overpressure, so persistently urged by Mr. Fairbairn, be the true explanation, boiler explosions may be entirely prevented, even where the attendants are guilty of the grossest carelessness. For with a sufficient area of effective safety-valve opening, it would be absolutely impossible, under the hardest firing, to raise the pressure 20 lbs. above the point at which the valves had been set to blow off. Safety-valves are simple, and comparatively inexpensive appliances,

and they should be so fitted so as to leave no doubt of their efficiency. Hawthorn's annular safety-valve, when its area is properly proportioned to the evaporative power of the boiler, renders any accumulation of pressure above the safe working limit quite impossible. Upon the locomotives of some of the Austrian railways, Baillie's 12-in. safety-valves, held down by volute springs pressing directly upon the valve, are in use. In a trial made in Vienna, to ascertain the discharging power of this kind of valve, the fire in a locomotive fire-box was urged by a jet of steam in the chimney, the engine being at rest, and 80 cubic ft., or $2\frac{1}{4}$ tons, of water were evaporated in one hour and discharged, in the form of steam, from the safety-valve. Although originally loaded to 64 lbs., the valve did not rise, during the experiment, above a point corresponding to a pressure of 76 lbs. per sq. in. The relief of pressure depends entirely upon the extent of safety-valve opening, supposing the valves to be in working order. Since the recent explosion of a lo-

comotive boiler on the Lewes branch of the Brighton Railway, Mr. Craven, the locomotive superintendent, has expressed his intention of applying three safety-valves, of the usual size, to each of his engines. Whilst it would be quite possible, with a boiler unprovided with safety-valves, or of which the valves were inoperative, to produce an explosion by overpressure, it would be equally impossible to do so when these outlets from the boiler were equal in discharging capacity to its evaporative power. The fact of explosion by sheer overpressure is a proof, simply, that the safety-valves were either inoperative or of insufficient size.

Explosion at Ordinary Pressures.—If an iron cylinder be burst by hydrostatic pressure, the broken parts are not projected into the air. The pressure being relieved by the rupture of the iron, it ceases to act before the ruptured parts can acquire momentum. In the case of a locomotive boiler bursting with only 75 cubic ft. of steam, of a pressure of 140 lbs. per square inch, there would be a considera-

ble expansive action after the plates were rent open. But this amount of steam, if expanded 685 cubic ft., equal to the volume of a sphere 11 ft. in diameter, before its pressure was reduced to that of the atmosphere, could hardly produce any very violent effects. So much of it would escape on the first opening of a seam of rivets, or other outlet, that a great part of the steam would be gone before the parts of the boiler could be completely separated. The range of action of this amount of steam would also be comparatively short, as it would have to expand only about nine-fold before all its expansive power would be gone. It is altogether improbable that, if steam only, of 140 lbs. to the square inch, were let into a close vessel calculated to burst at that pressure, the explosion would have the violence of a boiler-explosion under the usual circumstances. The laws of expansion of compressed air are nearly the same as those of steam, and vessels employed in pneumatic apparatus are occasionally exploded, with an audible report

and a smart shock, it is true, but without that terrible energy in which steam-boiler explosions so much resemble the explosion of gunpowder. Steam cylinders sometimes fail; generally, however, from the concussion of the piston against water collected in the cylinder; but in such cases, with steam of nearly the full boiler pressure, and although the cylinder is formed of brittle cast iron, the broken parts are not projected violently away. In order to project bullets by steam, Jacob Perkins employed pressures of from 300 lbs. to 950 lbs. per square inch, whilst one ounce of fine powder, to the detonation of which steam-boiler explosions are so frequently compared, will project a 24 lbs. ball 300 yards; 225 yards being the least range, in such a proof, at which the powder is received into the service. But whatever may be the force of steam acting by itself, the sudden liberation of the heat, stored up, under pressure, in a considerable quantity of water, as in a boiler-explosion, would develop an additional force. If, upon investigation, this

force appears to be sufficient to account for the violent explosion of steam-boilers, after rupture has once commenced, in consequence of defective material or construction, and, as we may suppose, under an ordinary pressure, we shall not need to assume and to account for the existence of extraordinary pressures like those with which Mr. Perkins experimented. If we consider heat as the source of power, and that the action of heat upon matter is always attended by the production of power, we shall be enabled to form a tolerable idea of the force concealed in a large body of highly heated water. The mechanical theory of heat has now attained such general acceptance, that it is sufficient to bear in mind that the "unit of heat," or the total quantity of heat capable of raising the temperature of one English pound of water through one degree of the Fahrenheit scale—or, which is the same thing, that of 100 lbs. of water through .01 of a degree, or .01 lb. of water through 100 deg.—that this quantity of heat, inde-

pendently of the medium through which it is exerted, possesses the same amount of power as would be required to raise 772 English pounds through a space of one English foot, or 1 lb. through 772 ft., or 772 foot-pounds. If the addition of one degree of temperature to one pound of water be an addition of such a force, the addition of 100 deg. to 10,000 lbs. of water is an addition of 1,000,000 times the same force. In actual practice, the combustion of a pound of coal imparts to the water in a steam-boiler about 10,000 units of heat, equal to the evaporation of 8 lbs. or 9 lbs. of water of ordinary temperature; and as in ordinary working, and under many losses and disadvantages, a pound of coal exerts about one-fourth of one horse-power for one hour, or 15 horse-power for one minute, or 900 horse-power for one second, the heat stored up in 10,000 lbs. of water, in raising it through 100 deg. of temperature, is practically and actually equal to 25 horse-power exerted for one hour, or 1,500 horse-power exerted for one

minute, or 90,000 horse-power exerted for one second! The heating of 10,000 lbs. of water through 100 deg. of temperature represents but a small part of the heat contained in an ordinary steam-boiler; yet it practically requires the combustion of 100 lbs. of coal to effect it, and the heat imparted is equal to that expended in the conversion of about 870 lbs. of water, of ordinary temperature, into steam. In a boiler explosion the contained heat is all disengaged in perhaps one or two seconds.

Recurring to the locomotive boiler, with 75 cubic ft. of water space and 75 cubic ft. of steam-space, the corresponding weight of water would be 4,650 lbs., whilst the steam, even at 140 lbs. pressure, would weigh only 26 lbs. The temperature of this steam, however, which is the temperature also of the water from which it is formed, is 361 deg., and the water is heated therefore 149 deg. above the temperature at which it would produce steam, in the open air, of atmospheric pressure. Water could

only be heated to this temperature by being confined under a corresponding pressure, and if, when the water has been so heated, the pressure is removed, the water cannot remain in its original condition as water merely, but a part of it becomes immediately converted into steam. 4,650 lbs. of water, heated to 361 deg., contains as much heat, or as many "units of heat," over and above the heat at which it gives off steam of atmospheric pressure, as are contained in 577 lbs. of steam of a total temperature of 1,200 deg. It is fair to presume, therefore, that upon the sudden liberation of the pressure under which 4,650 lbs. of water had been heated to 361 deg., about 577 lbs. of it would be immediately converted into steam. This quantity is more than twenty-two times greater than that of the steam originally contained in 75 cubic ft. of space, and at a pressure of 140 lbs. per sq. in.

If we suppose a considerable rupture of any part of the boiler, anywhere above the water-line, the steam already

formed would rush out with a velocity at first of about 2,000 ft. per second. Before the heat, contained in the water, could so far overcome the inertia of the water as to disengage additional steam, the upper part, or steam-space of the boiler, might be nearly emptied. The steam which would inevitably rise from the water would thus strike at a very great velocity upon the upper part of the boiler, and no doubt, as Mr. D. K. Clark has suggested, in a communication to the "Mechanics' Magazine," of 10th February, 1860, the steam carries a great quantity of water with it. In some of the earlier locomotives, having a deficiency of steam room, the partial removal of the pressure from the water, by opening the regulator or "throttle," was attended by a rise of the water to the extent of from 8 to 10 in. But whilst this result attended the removal of perhaps $\frac{1}{20}$ of the superincumbent pressure, its sudden and entire removal would cause a tremendous blow to be discharged—whether by the steam alone

or by the combined steam and water—upon the sides of the boiler, sufficient, no doubt, not only to extend the rupture already existing, but to completely rend the boiler in two or more parts. In the case of the explosion at Birmingham, on the 5th March, 1857, of engine No. 175, belonging to the Midland Railway Company, the boiler was broken into 17 pieces. These effects would follow when the boiler had ruptured, in consequence of some defect in its structure, under a moderate working pressure, as well as under such immense pressures as are commonly assumed in cases of violent explosion. There is reason to believe that steam alone, striking at a great velocity upon a solid surface, can discharge a violent blow, in addition to whatever effect it may produce by its pressure when at rest. Mr. D. K Clark has mentioned to me that where he had applied an indicator to a locomotive cylinder in which there was little or no compression, the sudden admission of steam through a large steam-port not

only carried the pencil of the indicator above the point corresponding with the highest pressure in the steam-chest, but a positive blow was discharged upon the finger when placed upon the pencil-holder of the indicator. The same gentleman has mentioned to me also a fact which has been observed in the working of the Cornish engines, where steam of moderately high pressure is admitted into large cylinders, sometimes 100 in. in diameter. The cylinder covers are found to "spring" with each admission of steam, indicating a smart shock in addition to the pressure, which, after the piston has commenced its stroke, can only act statically upon the cylinder cover. Some years ago, and before the days of steam-gauges, one Signor Morosi maintained the extraordinary opinion that on the stoppage of the piston at each end of its stroke, the whole force of the steam was so violently stopped in its motion as to strike back forcibly into the boiler, like the water in the hydraulic ram, impinging as would a solid

body upon the boiler plates.* The percussive action of steam is certainly not so great as this; for it is only when steam strikes through an intervening space upon an unyielding surface and with a velocity of several hundred feet per second, that it can be considered to act with any amount of percussion worth mentioning, and not when reacting (if indeed it did react) against a large body of steam within a boiler, and at the slow speed of a steam-engine piston, gradually extinguished as its motion is at each end of its stroke. And, of course, upon Signor Morosi's notion, the boiler should explode, if at all, when the engine makes its first stroke. In practice, the steam-gauge, which has since come into general use, is found to indicate a constant pressure without reference to the changing of the strokes of the piston, excepting where the steam-room of the boiler is very much too small.

But the momentum of the combined

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* Dr. Alban on the "High-pressure Steam-engine," translated by Wm. Pole (p. 27). London: Weale, 1848.

steam and water, discharged, as Mr. Clark has suggested, in his communication already referred to,* would probably be sufficient to overcome the resistance of the material of the boiler and to rend it open, not only along seams of

* The following is a copy of Mr. Clark's letter:

"TO THE EDITORS OF THE "MECHANICS' MAGAZINE."

11 Adams Street, Adelphi, London, Feb. 9, 1860.

GENTLEMEN,—I have within the last few months given some attention to the subject of boiler explosions—their causes, and their *rationale*. I observe, in the discussions that have appeared in contemporary papers, that the percussive force of the steam suddenly disengaged from the heated water in a boiler, acting against the material of the boiler, is adduced in explanation, and as the cause of the peculiar violence of the result of explosion.

Now, gentlemen, a little calculation would show that the percussive force of steam is not capable of causing such destructive results as are occasionally produced; and I beg leave to suggest that the sudden dispersion and projection of the water in the boiler against the bounding surfaces of the boiler is the great cause of the violence of the results: the dispersion being caused by the momentary generation of steam throughout the mass of the water, and its efforts to escape. It carries the water before it, and the combined momentum of the steam and the water carries them like shot through and amongst the bounding surfaces, and deforms or shatters them in a manner not to be accounted for by simple overpressure or by simple momentum of steam.

Your obedient servant,

D. K. CLARK.

rivets, but, as is often the case, through solid iron of the strongest quality. The velocity with which the steam and water would strike would depend upon the extent to which the steam-space of the boiler had been emptied of steam, before the inertia of the boiler had been overcome by its contained heat. The water carried with the steam would not retain its ordinary condition as a liquid, but, being completely pervaded by nascent steam, would have the character of an expansive body of more or less elasticity. The destructive effects produced by the inevitable concussion of such a body upon the upper portion of a cylindrical boiler (and the water being originally in the bottom of the boiler would only strike upwards) cannot be estimated therefore by multiplying its weight, as if it were a solid body, into the velocity assumed to be acquired in the distance through which it would be projected against the iron shell of the boiler. It is very likely that the momentum of the steam and water is ex-

pended mainly in breaking the plates, especially through strong solid iron, and that if no additional force were afterwards brought into play the ruptured parts of the boiler would drop to the ground, or, at the most, be projected only to a short distance. But at the moment when the steam and water rise to the upper part of the boiler, and, indeed, until a large outlet is provided (as when, perhaps, the boiler is forced completely open), the quantity of steam disengaged will be very small indeed ; not greater than the quantity originally contained in the steam-space of the boiler. Whatever may be the quantity of heat in the water, it cannot convert any portion of the water into steam of a greater pressure than that under which only the water was originally heated ; that is to say, water heated, for instance, to 361 deg. cannot at that heat produce steam, spontaneously, of a greater pressure than 140 lbs. per sq. in. It is after the boiler has been rent completely open, and after its separated portions have,

perhaps, been started upon different courses through the air, that the great disengagement of steam from the heated water must take place. This phenomenon can only occur after the boiler has been rent completely open, or, at least, when the water is no longer confined within its original limits, because the original capacity of the boiler would be insufficient for the disengagement of the steam, which, as it can never rise much above its original density, can only disengage itself upon the expansion of the water in which it was previously confined. Assuming 577 lbs., or 9.25 cubic ft., of the water contained in the locomotive boiler, already described, to be converted into steam of atmospheric pressure, it would form 15,188 cubic ft. of steam, equal to the volume of a sphere of 31 ft. diameter ; and until the disengaged steam had expanded to this volume at least, the parts of the exploded boiler would be within the range of explosive action. Under the velocity with which, as in the explosion of large

boilers, more than one ton of elastic vapor would discharge itself into the air, the projection of fragments of the boiler, weighing 5 cwt., to a distance of 350 yards, as in the explosion at Wharton Colliery, near Chesterfield, in June, 1856, is not perhaps anything to be wondered at.

Under the foregoing explanation of boiler explosions their results are produced by a series of consecutive operations, the first of which is the rupture of some portion, generally a defective portion, of the shell of the boiler ; the rupture, unless it be of considerable extent, occurring generally—in cases of violent explosion—above the water-line. If a narrow rent take place in the bottom of the boilei the pressure upon the water will not be removed until the water falls to the level of the discharging opening ; and hence, as the water is not likely to escape with very great rapidity, no percussive action will occur within the boiler, from steam, either disengaged by itself, or in combination with water;

and the steam which is disengaged. from the escaping water will be already out of the boiler at the moment of its disengagement.

The distinct and consecutive operations into which a boiler explosion, although practically instantaneous, may probably be resolved, are, therefore, these :—

1. The rupture, under hardly if any more than the ordinary working pressure of a defective portion of the shell of the boiler ; a portion not much, if at all, below the water-line.

2. The escape of the free steam from the steam-chamber, and the consequent removal of a considerable part of the pressure upon the water, before its contained heat can overcome its inertia and permit the disengagement of additional steam.

3. The projection of steam, combined as it necessarily must be with the water, with great velocity and through a greater or less space, upon the upper sides of the shell of the boiler, which is

thus forced completely open, and perhaps broken in pieces.

4. The subsequent disengagement of a large quantity of steam from the heated water now no longer confined within the boiler, and the consequent projection of the already separated parts of the boiler to a greater or less distance.

The rapidity of the escape of the steam, through a narrow opening, may be understood practically by observing an indicator diagram, taken from a locomotive cylinder when the engine is running at a high speed. The driving-wheels, at high velocities, revolve between four and five times every second, and each cylinder must exhaust twice at each revolution, or perhaps ten times in 1 sec. An examination of the indicator diagram will show, moreover, that the actual exhaustion, at each half-revolution of the wheels, does not occupy much, if any, above one-fourth of the time in which such half-revolution is made—each complete exhaustion of a cylinder-full of high-pressure steam oc-

cupying, therefore, but about one-fortieth of 1 sec., notwithstanding the length and tortuous character of the exhaust passages, and the comparatively gradual opening of the valve.

The force with which steam in motion will take up and carry water with it may be seen in the "Automatic Injector," or feed-water apparatus, of M. Henri Giffard, as made by M. Flaud, of the Rue Jean Goujon, Paris, and more recently, by Messrs. Sharp, Stewart & Co., of Manchester, and the Rogers Locomotive and Machine Company, of Paterson, U. S. In this apparatus, a jet of steam discharged through a conical nozzle, draws up a considerable body of feed-water and impels it, first for a short distance through the open air, and thence, through a valve, into the same boiler from which the steam was originally taken. The under side of the clack valve—or so much of its under side as receives the impact of the water before the valve is raised from its seat—has, of course, less area than the upper side,

on which the pressure within the boiler is exerted. Hence, to force water into the boiler against a pressure of, perhaps, 120 lbs. per sq. in., a pressure of, probably, at least 175 lbs. per sq. in. of the under side of the valve, has to be first exerted by the jet of combined steam and water. The jet at the same time is very small, and must move with considerable friction, which, therefore, by so much diminishes its original force of motion.

Where, therefore, a rupture is not attended by explosion, it is to be presumed either that the relief of pressure is not so sudden as to induce percussive action by the steam spontaneously generated, or else that, even with the partial or total removal of the pressure, the quantity of heat stored up in the water is insufficient to complete the explosion. If a very small crack occur above the water-line, or if a considerable aperture be very gradually opened, the removal of the pressure upon the heated water will be so gradual that no violent percussive action

may be induced, and, as has been already observed, if the rupture occur below the water-line, the pressure upon the water may not be removed until it has been almost wholly discharged from the boiler. The dome covers of locomotive boilers are sometimes blown off without explosion, but here it is probable that the fastening bolts do not all give way at once, and that the opening for escape enlarges gradually before the cover is forced completely off. In 1853, the boiler of locomotive No. 4 of the New York and New Haven Railroad, ruptured along the junction of the barrel of the boiler with the dome. The steam was lost and the train detained, but no further damage was done. In the winter of 1856–7 the boiler of one of the locomotives of the New York and Harlem Railroad ruptured through the underside of the cylindrical barrel, the results being similar to those just mentioned.

Another case, which came under my own observation, was that of a locomotive fire-box, which was ruptured at the

Dunkirk shops of the New York and Erie Railroad. One seam of rivets had opened, on the outside fire-box, 1 in. in width, and perhaps 2 ft. in height. The further opening of the seam had been prevented by the framing of the engine, which extended along the side of the fire-box. No violent consequences attended this rupture. In his last report, H. W. Harman, C. E., Chief Inspector to the Manchester Boiler Association, states that in one case which occurred under his inspection, an oval flue collapsed with complete rupture of the plates, in consequence of the gradual admission of steam through the stop-valve of an adjoining boiler, and of higher pressure than the flue was capable of sustaining. "But," adds Mr. Harman, "no explosion occurred; it came quietly down, and the contents were discharged into the boiler house without any report whatever; and in another case arising from deficiency of water, the plates became overheated and flattened sufficiently to derange the seams, and a

portion of the water escaped, also without concussion."

As already observed, the percussive action exerted by the combined steam and water, upon the sudden removal of the pressure, must be exerted mainly upwards, and probably the larger number of exploded boilers first give way in the upper part of the barrel. Comparatively few locomotive boilers ever leave the rails when they explode, unless the roof of the inside fire-box is crushed down. In February, 1849, the boiler of a locomotive employed on the Boston and Providence Railroad, United States, exploded with great violence whilst the engine was running with its train, and just after the steam had been shut off in approaching the Canton station. The engine did not leave the rails, but ran some distance after the explosion. The explosion of engine No. 58, upon the New York and Erie Railroad, in the summer of 1853, was attended with much the same results. The engine Wauregan, the explosion of which has been already mentioned, was

not moved from the rails. Locomotive No. 77, of the New York Central Railroad, exploded in the winter of 1856–7, whilst running with a train, and just after the steam had been shut off. The engine did not leave the rails. Much of the iron in the barrel of the boiler was nearly as brittle as cast iron. Engine No. 23, of the Baltimore and Ohio Railroad, exploded violently at about the same time and in nearly the same manner. The engine of which the boiler burst in Messrs. Sharp, Stewart & Co.'s Works, in the summer of 1858, was not thrown from the rails, although the explosion was one of terrific violence. Nearly all of these explosions occurred in the waist of the boiler, towards the smoke-box end. In but one of the six explosions just mentioned was there any evidence of the overheating of any portion of the boiler. The tubes were in nearly every case bulged outwards beyond the original diameter of the boiler, showing that in the disengagement of steam from the water contained among

them a considerable outward pressure had been exerted; although the closeness of the tubes, and the consequent want of any clear space through which the disengaged steam could strike, precluded the supposition of percussive action, which, indeed, had it occurred, would have broken the tubes to pieces, and driven them in every direction, instead of bending them merely.

In the case of the locomotive Irk, which exploded in the Manchester engine-shed of the Lancashire and Yorkshire Railway, in February, 1845; in that of the explosion at Rogers, Ketchum & Grosvenor's in May, 1851; in that of engine No. 100, which exploded on the New York and Erie Railroad, in 1852 I believe, and in the case of the explosion of an agricultural engine, at Lewes, Sussex, in September last, the roof of the fire-box was in each case forced downwards, the steam discharging below, and the engine was, in every instance, thrown into the air. Considering that the ordinary pressure upon the crown-plate of

a locomotive fire-box is from 80 to 150 tons, there is no difficulty in accounting for these results, after the plate has once gone down.

The boiler explosion which occurred at Messrs. Warburton & Holker's Works near Bury, on the 15th of August, 1856, was believed to have commenced in the bottom of the boiler. An extensive crack was known to have existed there, and it had been twice patched, notwithstanding which, a considerable breadth of iron was afterwards found to have been reduced to a thickness of only $\frac{1}{16}$ in. But as the boiler was 36 ft. 6 in. long, and no less than 9 ft. 1 in. (109 in.) in diameter, and as it was worked, after its $\frac{3}{8}$th in. plates had been 11 years in use, at a pressure of 40 lbs. per sq. in., the final rupture of the bottom was in all probability instantaneous for a great length, especially as the boiler was riveted up with continuous seams, or seams which did not break joints with each other! This huge bomb-shell was said to have contained 56 tons of

water at the moment of explosion; which quantity heated to 287 deg., corresponding to the pressure at which the explosion took place, would have given off at least $3\frac{1}{2}$ tons of steam! It has, indeed, been assumed, that in many cases of explosion, all the water previously contained in the boiler is converted into steam. Mr. Edward Woods once mentioned, at the Institution of Civil Engineers, an instance which came under his observation, in 1855 I believe, and where, after a locomotive boiler had burst, the whole of the water was found to have completely disappeared. Mr. Vaughan Pendred, of Dublin, has informed me that he observed a similar result after he had exploded a small boiler, well supplied with water, for the purpose of experiment. He had erected a fence of boards about the place where the boiler was allowed to burst, but on going to the spot immediately afterwards no traces of water could be seen. I cannot adopt the idea, however, that all the water, heated, probably, to less than 400 deg., is actu-

ally converted into steam. It is, no doubt, dispersed in a state of minute division and to a great distance ; but the greater portion of it must still maintain its existence as water, since its contained heat is insufficient to convert it into steam. But there can be no doubt of the sudden generation of steam and projection of the water, when the pressure, under which water has been heated, is suddenly removed, and it is probable that water, heated in the open air to 212 deg., would be sufficient to produce violent explosion if suddenly placed in a vacuous space, corresponding, in its proportions to the contained water, to an ordinary boiler. A boiler, 24 ft. long and 10 ft. in diameter, burst with great violence on the 9th December, 1856, at Messrs. Cresswell & Son's ironworks, at Tipton. In this case it was observed that the floor of the boiler house, immediately after the explosion, was covered with water, and this fact was taken as evidence of a sufficiency of water in the boiler. The boiler had been in use for some 18 years,

but its plates had retained an average thickness of $\frac{3}{8}$ in. Had the plates been of good quality originally, and had they suffered no deterioration in the long time during which the boiler had been worked, the bursting pressure would have been 167 lbs. per sq. in. The explosion of the boiler was attributed to overpressure, although the regular working pressure was but 17 lbs. per sq. in.

The idea has been already suggested that heated water, if suddenly placed in a vacuous space, would disengage steam with great violence. The result would be necessarily the same whether the pressure, under which the water had been heated, were suddenly removed by exhaustion or by condensation. And if it were purposely sought to condense the steam in the upper part of a boiler, this could be effected with lightning-like rapidity. When steam of considerable pressure is discharged into a condenser of suitable capacity, the condensation is so instantaneous that the index of the vacuum gauge does not move at all.

Even in surface condensers, in which the steam is let in upon several hundred square feet of tubular surfaces, kept cool by a constant circulation of water, the same instantaneous action takes place. If, therefore, a sufficient quantity of cold water—or water considerably below the boiling point corresponding to the pressure—were suddenly thrown up among the steam, its condensation would as suddenly take place. An instant can thus be conceived in which no pressure would exist upon the water, which, as soon as its inertia could be overcome by its contained heat, would, therefore, be thrown violently against the upper part of the boiler, causing its explosion in the manner already explained. Whether, in the practical working of a steam-boiler, circumstances ever arise in which such condensation could occur, is a matter of conjecture. In locomotive engines, for example, the feed water is commonly pumped into the boiler at two points on either side, a little below the ordinary water level. With both pumps on, from

100 to 175 cubic inches of water are pumped in at each revolution of the driving wheels; and at a speed of even 30 miles an hour, from 10 to 15 cubic feet, or from 600 lbs. to 1,000 lbs. of water would be pumped in every minute. If this water were pumped in at the water level, it might not, obstructed as its descent would be by the closely packed tubes, mix with the water already in the boiler, until after some minutes; especially if the engine were running by momentum only, after the steam had been shut off, and when, therefore, but very little steam would be in process of generation, and when the circulation of the water would be consequently sluggish. If a stratum of cool water were to accumulate over the tubes, it would require a long time to heat it, especially if the draught had been stopped by shutting off the steam. Indeed 10 cubic feet of feed water, without circulation and consequent mixture with the hot water already in the boiler, would not, even when in contact with the heating sur-

faces, become heated to the boiling point in much less than a quarter of an hour. As long, however, as this water remained quiescent, the steam accumulated over it would be condensed only very slowly. But if, as by suddenly turning the steam again into the cylinders, the diminution of pressure, and consequent rise of water, were such as to throw up a considerable quantity of it into the steam-chamber, the free steam might be instantly condensed, and, in such case, the reasoning already adopted would support the probability of instant explosion. In this case, the actual occurrence of which is not, perhaps, impossible, it would not be necessary to assume the existence of any defect in the boiler; for, when the water once struck violently, the soundest iron would probably be broken, and the strongest workmanship destroyed.

Locomotive boilers often burst in the plates next to the smoke-box, beyond the reach of the fire, and where the boiler is believed to be stronger than about the fire-box. As has been observed, the dome,

if it open from the ring of plates in question, weakens it materially; but explosions have occasionally occurred in this part of a boiler, either having no dome, or having one only over the fire-box. A fact which was some time since communicated to me by George S. Griggs, Esq., Locomotive Superintendent of the Boston and Providence Railroad, U. S., may assist in explaining this somewhat anomalous mode of explosion. In one or two cases of locomotive boiler explosions, Mr. Griggs found, upon examination, that whilst none of the upper tubes had been burnt, others, lower down, exhibited unmistakable indications of having been smartly scorched; the solder used in brazing being more or less melted. The tubes being closely packed in the boiler, it appeared that the heat passing through them had dispersed the water from their sides; the water level being but about 15 in. above, and the consequent pressure of water, resulting from this amount of "head," being only

about one-half pound per square inch to overcome the violent disengagement of steam in the restricted passages below. The admission of water through the "check-valve" of the pump would suddenly cool the parts of the boiler with which it came first in contact, and would, no doubt, cause the partial return of the water to the surfaces from which it had been expelled. Sufficient steam might be thus disengaged, by 2 cwt. or 3 cwt. of highly heated copper or brass tubes, to exert a sudden and powerful strain upon the surrounding parts. Mr. C. Wye Williams has mentioned, in his work on the Combustion of Coal, a circumstance similar to that observed by Mr. Griggs. In one of the deep and narrow water-spaces of the boilers of the Great Liverpool steamship, the engineer found, on the first trip of that vessel to New York, in 1842, that the side plates were constantly giving way. On tapping a gauge-cock into the space, several feet below the water level, only steam was discharged, although the water was,

at the same time, standing several feet above. In nearly all American and in the majority of French locomotives, of recent construction, the tubes are disposed in vertical rows, in order to assist the circulation of the water. Mr. Griggs has assured me that some of his engines, with closely packed tubes, have actually made steam more freely after he had plugged the ends of ten or a dozen tubes, one over the other, in the middle of the boiler. As long as the water was not in complete contact with these tubes, the heat which before passed through them was to a greater or less extent lost. I have myself observed that a class of locomotives having 130 tubes, 2 in. in diameter, made steam more freely than another class, in all respects the same, with the exception of having 144 tubes, $1\frac{3}{4}$ in. in diameter, although the actual extent of heating surface was hardly more in the former than in the latter case.

The quantity of water contained in steam-boilers of a given length, and the

consequent quantity of explosive matter which they contain under any given pressure, is, practically, as the square of their diameters; and although different boilers, of the same materials and workmanship, are believed to be equally strong to resist rupture when the thickness of their plates bears the same ratio in every case to their diameter, the real danger, which ensues after rupture has actually commenced, may be estimated, so to speak, as the square of their diameter and directly as their length, or, in other words, as directly proportional to the quantity of water which they contain at any given temperature. Although locomotive boilers, perhaps, sustain a greater proportionate strain than ordinary land boilers, and are, for that reason, somewhat more liable to explosion, the effects resulting from their explosion are seldom anything like those which attend the destruction of large land boilers, even when working at very moderate pressures. The Great Eastern casing, which exploded with great vio-

lence on the trial trip last September, was no more than a large boiler, 7 ft. in diameter, with an internal flue of 6 ft. diameter, and which was, practically, unstayed. The collapse of this flue, under a moderate pressure, and the consequent liberation of the heat contained in the hot feed-water, of which the casing was made to hold 11 tons, was sufficient, upon the explanation herein advanced, to account for the disastrous character of the explosion.

I think there can be no doubt that a consideration of the expansive power of a large body of highly heated water, acting under the instigation of a sudden removal of the pressure (with the aid of which only it was possible to heat it above 212 deg.), is capable of clearing up much of the mystery which has for so long a time enshrouded the subject of Boiler Explosions. Such a consideration leads to a comprehensible and rational explanation of these disasters; one which, upon a rigid process of reasoning, appears sufficient to account for all

or nearly all cases of the kind. Whilst the present essay may serve to commend this explanation to engineers and to the public generally, I hope it may also hasten the adoption of smaller and more numerous water-spaces in steam-boilers, as in the water-tube arrangement, which, with pure water, is, in my opinion, the safest, most efficient, and most economical yet devsed for the generation of steam. But, above all else, public safety requires the frequent and systematic examination of all steam-boilers, so that, as under the system of inspection which is in operation with such excellent results at Manchester and Huddersfield, defects may be discovered and remedied, in most cases before actual danger has been incurred.

All our knowledge of boiler explosions goes to show that, however possible it may be to accumulate an excessive pressure within a boiler, the actual explosion results, in the majority of cases, from some defect, either original or produced, and either visible or concealed, in the

materials, workmanship, or construction of the boiler. Probably not much more than one per cent. of all the steam boilers made ever explode at all, and the results of systematic inspection show that a far higher percentage of the whole number of boilers are constantly in a condition inviting explosion, and from causes which a general examination would not only disclose, but of which it would also insure the removal.

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